

Magnetotransport study of the charged stripes in high- T_c cuprates

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We present a study of the in-plane and out-of-plane magnetoresistance (MR) in heavily-underdoped, antiferromagnetic $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$, which reveals a variety of striking features. The in-plane MR demonstrates a “ d -wave”-like anisotropy upon rotating the magnetic field H within the ab plane. With decreasing temperature below 20-25 K, the system acquires memory: exposing a crystal to the magnetic field results in a persistent in-plane resistivity anisotropy. The overall features can be explained by assuming that the CuO_2 planes contain a developed array of stripes accommodating the doped holes, and that the MR is associated with the field-induced topological ordering of the stripes.

1. INTRODUCTION

The conducting state of the high- T_c cuprates appears as a result of hole or electron doping of the parent antiferromagnetic (AF) insulator. In general, there is a tendency of doped holes in the AF environment to phase-segregate, which may give rise to an intriguing microscopic state with carriers gathered within an array of quasi-1D “stripes” separating AF domains [1–3]. An ordered striped structure has been observed in $\text{La}_2\text{NiO}_{4.125}$ (Ref. [4]) and in $\text{La}_{1.6-x}\text{Nd}_{0.4}\text{Sr}_x\text{CuO}_4$ (Nd-LSCO, Ref. [5]), while most superconducting cuprates demonstrate incommensurate magnetic fluctuations [6] which can be considered as *dynamical* stripe correlations [1,6]. The dynamical stripes might be responsible for the peculiar normal state of cuprates as well as for the occurrence of superconductivity [1], but still very little is known about the electron dynamics in the stripes.

In this paper, we report an extraordinary behavior of the magnetoresistance (MR) in antiferromagnetic $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ (YBCO), which provides evidences that conducting stripes actually exist in CuO_2 planes and have a considerable impact on the electron transport. We note that a recent study of the Hall effect in Nd-LSCO also

provides insights into the electron transport in static stripes [7].

2. EXPERIMENTAL

The high-quality YBCO single crystals were grown by the flux method in Y_2O_3 crucibles, and a high-temperature annealing was used to reduce their oxygen content. The MR was measured by sweeping the magnetic field at fixed temperatures stabilized by a capacitance sensor with an accuracy of ~ 1 mK. The angular dependence of the MR was determined by rotating the sample within a 100° range under constant magnetic fields up to 16 T.

3. RESULTS

The heavily-underdoped YBCO crystals, though located deep in the AF range of the phase diagram ($x \approx 0.3$), are far from conventional insulators: the in-plane resistivity ρ_{ab} remains “metallic” at high T and it grows slower than expected for the hopping electron transport at low T [8,9]. These AF crystals demonstrate an unusual behavior of the in-plane MR, $\Delta\rho_{ab}/\rho_{ab}$, when the magnetic field H is applied along the CuO_2 planes, as shown in Fig. 1. At weak fields, the longitudinal in-plane MR [$H \parallel I \parallel ab$] is negative and follows roughly a T -independent ζH^2 curve, and then abruptly saturates above some threshold field. The threshold field and the saturated

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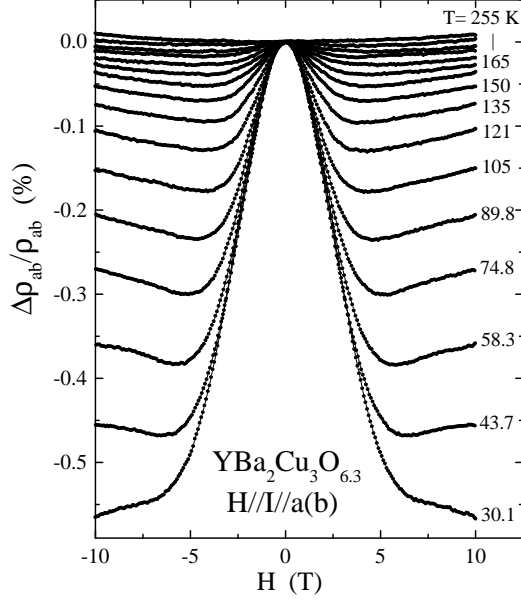


Figure 1. Longitudinal in-plane MR of YBCO in the antiferromagnetic composition. The data are averaged over several field sweeps.

MR value gradually increase with decreasing temperature. The MR anomaly becomes noticeable near the Néel temperature $T_N \approx 230$ K (T_N can be obtained from the $\rho_c(T)$ data, as reported in Ref. [8,10]), but evolves rather smoothly through T_N , which indicates that the long-range AF order itself is not responsible for its origin [9].

When the magnetic field is turned in the plane to become perpendicular to the current [$H \parallel ab$; $H \perp I$], the low-field MR term just switches its sign, retaining its magnitude and the threshold-field value [9]. This can be graphically shown in the MR data taken upon rotating H within the ab plane, which revealed a striking anisotropy with a “ d -wave”-like symmetry; i.e. $\Delta\rho_{ab}/\rho_{ab}$ changes from negative at $\alpha=0^\circ$ to positive at $\alpha=90^\circ$, being zero at about 45° (α is the angle between H and I), see Fig. 2. It is worth noting that the low-field MR feature is not observed at all when the magnetic field is applied along the c -axis.

The most intriguing peculiarity of the low-field MR appears at temperatures below ~ 25 K, where

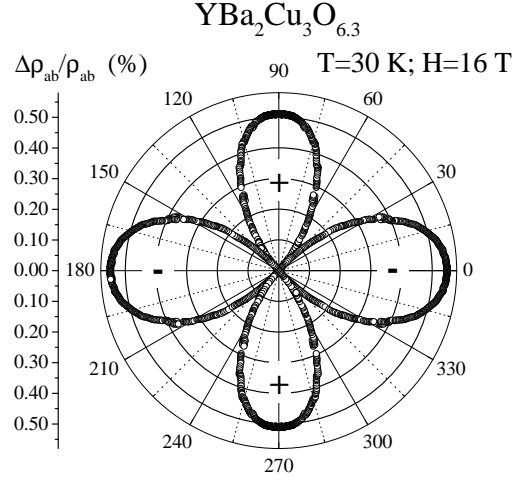


Figure 2. Dependence of the in-plane MR on the angle between H and I ($H \parallel ab$; $H=16$ T). The sign of the MR is indicated.

the H -dependence of ρ_{ab} becomes irreversible. Figure 3 shows the low-field MR term measured for $H \perp I$ (for clarity, the background MR, γH^2 , determined at high fields, is subtracted: $\Delta\rho_{ab}/\rho_{ab} = (\Delta\rho_{ab}/\rho_{ab})^* + \gamma H^2$). Initially the irreversibility appears as a small hysteresis on the MR curve; however, upon cooling to 10 K it becomes much more pronounced (the MR peaks are shifted from $H=0$ and strongly suppressed). We note that the first field sweep, which starts at $\Delta\rho_{ab}/\rho_{ab}=0$, differs significantly from the subsequent ones. The salient point here is that the resistivity does not return to its initial value after removing the magnetic field; hence, the system acquires a memory. In other words, the application of the magnetic field at low T induces a persistent resistivity anisotropy in the CuO_2 planes.

The picture would be incomplete without the data on the c -axis transport (across the CuO_2 planes). It was shown that in antiferromagnetic YBCO below T_N , the suppression of spin fluctuations by the magnetic field results in a large positive out-of-plane MR [10]. Figure 4 shows an intriguing MR behavior produced by a superpo-

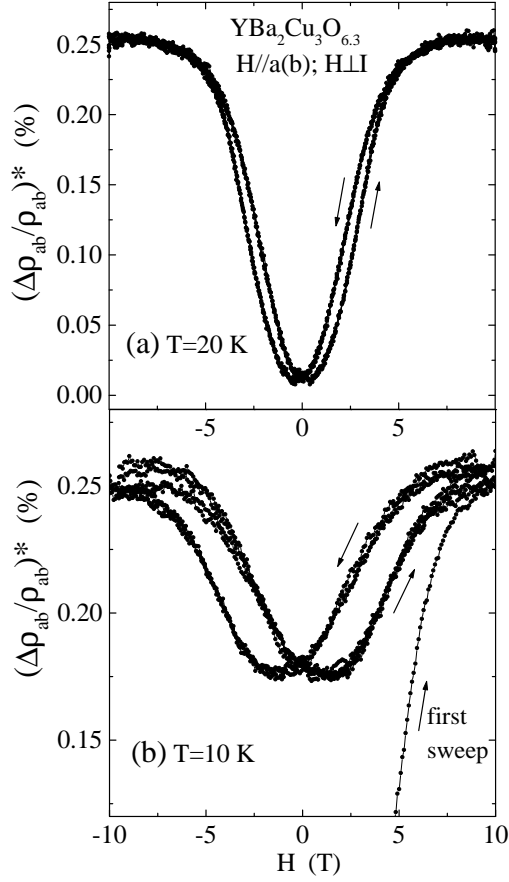


Figure 3. The low-field MR component. Each curve contains data of 4 field sweeps performed at a rate of 1 T/min.

sition of the negative low-field MR feature on top of the large positive γH^2 background in a sample with $T_N \geq 300$ K.

4. DISCUSSIONS

It is very difficult to understand the MR anomalies presented here, especially the *memory effect*, without considering an inhomogeneous state or a superstructure in the CuO_2 planes instead of a uniform AF state. The picture of charged “stripes” in the CuO_2 planes allows one to account for all the observed MR peculiarities, by assuming that the magnetic field gives rise to

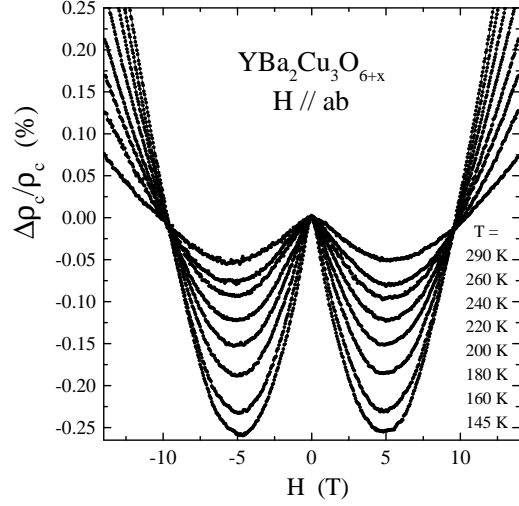


Figure 4. Transverse out-of-plane MR of YBCO in the AF composition, with $x \approx 0.28$.

a directional ordering of the stripes [9]. Actually, the aligning of stripes with confined carriers moving along would change the current paths and introduce the in-plane anisotropy. The rotation of stripes by the magnetic field gives a reasonable explanation for the in-plane MR with the d -wave-shaped angular dependence. Within this picture, the threshold field of several Tesla is presumably coming from the establishment of the directional order of the stripes.

As the temperature is lowered, it is expected that the stripe dynamics slows down and the magnetic domain structure in the CuO_2 planes is frozen, forming a cluster spin glass. The spin-glass transition temperature has been reported to be about 20-25 K for the AF compositions [11], which is in good agreement with the temperature where the hysteretic MR behavior is found.

Though an explanation of the out-of-plane MR feature is not so straightforward, one can imagine that by adjusting the direction of the stripes in neighboring CuO_2 planes, the magnetic field increases the overlapping both between the stripes in the real space and between their quasi-1D carriers in the k -space, thereby enhancing the probability of the electron hopping.

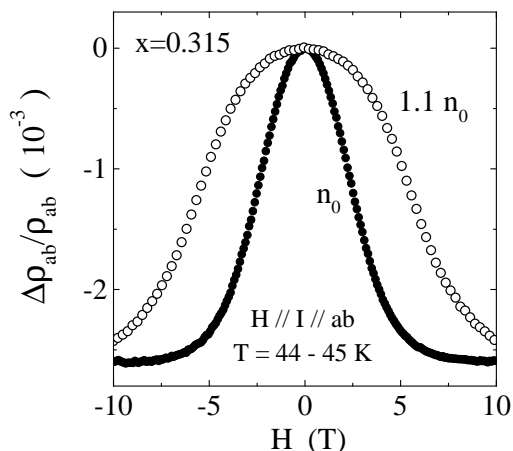


Figure 5. Longitudinal in-plane MR for two different carrier densities measured on the same sample ($x=0.315$) before and after oxygen ordering. Solid circles show the data for the initial carrier density (n_0), and the open circles show the data for $\sim 10\%$ larger carrier density.

One may wonder how the MR anomaly evolves when the carrier density is increased, bringing the system to more metallic region. Figure 5 shows the comparison of the MR data for two different carrier densities; the data were taken on the same sample, where the $\sim 10\%$ increase in the carrier density was achieved by keeping the sample at room temperature, which causes the oxygen re-ordering. It is clear that the threshold field for the stripe ordering increases with increasing carrier density. The data in Fig. 5 suggest that the threshold field becomes inaccessibly high when the carrier density is increased to the superconducting region ($x > 0.4$). This is probably the reason why the MR anomaly reported here has never been observed in superconducting samples.

5. CONCLUSION

A variety of unusual MR features found in heavily underdoped YBCO have provided new information on the conducting charged stripes in the CuO_2 planes. The MR behavior implies that the stripes couple to the external magnetic field

and undergo topological ordering at fields of the order of a few T, although the actual mechanism that couples the stripes to the magnetic field is not clear yet. Upon cooling the sample below ~ 20 K, the dynamics of stripes slows down and the directional order of the stripes becomes persistent, giving rise to a “memory effect” in the resistivity. These findings show that the magnetic field can be used as a tool to manipulate the striped structure and open a possibility to clarify the electron dynamics within the stripes.

REFERENCES

1. V. J. Emery, S. A. Kivelson, and O. Zachar, Phys. Rev. B 56 (1997) 6120.
2. E. L. Nagaev, Usp. Fiz. Nauk 165 (1995) 529.
3. F. Borsa *et al.*, Phys. Rev. B 52 (1995) 7334.
4. J. M. Tranquada *et al.*, Phys. Rev. B 52 (1995) 3581.
5. J. M. Tranquada *et al.*, Phys. Rev. B 54 (1996) 7489.
6. K. Yamada *et al.*, Phys. Rev. B 57 (1998) 6165.
7. T. Noda, H. Eisaki, and S. Uchida, Science 286 (1999) 265.
8. A. N. Lavrov, M. Yu. Kameneva, and L. P. Kozeeva, Phys. Rev. Lett. 81 (1998) 5636.
9. Y. Ando, A. N. Lavrov, and K. Segawa, Phys. Rev. Lett. 83 (1999) 2813.
10. A. N. Lavrov, Y. Ando, K. Segawa and J. Takeya, Phys. Rev. Lett. 83 (1999) 1419.
11. C. Niedermayer *et al.*, Phys. Rev. Lett. 80 (1998) 3843.